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AFRL-SR-BL-TR-02-

0737

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE		3. REPORT NUMBER	
				14 FEB 99 - 29 NOV 01	
4. TITLE AND SUBTITLE Energy Efficient Network Protocols for Wireless and Mobile Networks				5. FUNDING NUMBERS F49620-99-1-0125	
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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFOSR/NM 801 N. Randolph Street Room 732 Arlington, VA 22203-1977				10. SPONSORING/MONITORING AGENCY REPORT NUMBER  F49620-99-1-0125	
11. SUPPLEMENTARY NOTES					
12a. DISTRIBUTION AVAILABILITY STATEMENT APPROVED FOR PUBLIC RELEASE, DISTRIBUTION UNLIMITED				12b. DISTRIBUTION CODE 12. DISTRIBUTION IS UNLIMITED.	
13. ABSTRACT (Maximum 200 words) This research project studies the design, analysis and implementation of energy efficient (also called power aware) network protocols for woreless and mobile networks. Battery power limitations are a very serious concern, and it is essential to study energy efficient protocol design at different layers of the network protocol stack. In particular, we focus on the medium access control, scheduling, quality-of-service reservation signaling, and transport protocols. We completed the design and implementation of signaling mechanism will enable mobiles to inform the base station of the current battery powers levels. The signaling mechanism was based on the "Integrated Services" (intserv) and "Differentiated Services" (diffserv) Quality of Service (QOS) architectures. We developed and implemented routing algorithms to accomdate user mobility and integrated them with the signaling mechanism. We completed work on scheduling algorithms for wireless data networks with multiple channels per cell. Adaptive energy efficient scheduling algorithms that dynamically schedule the transmission channel to mobiles based on traffic requests and battery power levels of mobiles were developed and studies. We developed novel error compensation algorithms that enable mobile host to dynamically adapt to channel errors-previous work considered only the base station adapting to channel errors.					
14. SUBJECT TERMS				15. NUMBER OF PAGES 9	
				16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT		18. SECURITY CLASSIFICATION OF THIS PAGE		19. SECURITY CLASSIFICATION OF ABSTRACT	
				20. LIMITATION OF ABSTRACT	

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## 2 OBJECTIVES

This research project studies the design, analysis and implementation of energy efficient (also called power aware) network protocols for wireless and mobile networks. Battery power limitations are a very serious concern, and it is essential to study energy efficient protocol design at different layers of the network protocol stack. In particular, we focus on the medium access control, scheduling, quality-of-service reservation signaling, and transport protocols.

The research considered two different types of networks: *infrastructure networks*, where a central base station coordinates the mobile users' network communications, and *self-organizing networks* where the mobile users form a self-organized network of which a specific example is wireless sensor networks.

The research methodology consisted of rigorous and detailed performance analysis based on three techniques: mathematical modeling, discrete-event simulation based modeling and experimental implementation (where feasible) on a wireless testbed of the developed protocols and algorithms.

## 3 ACCOMPLISHMENTS/NEW FINDINGS

The following paragraphs summarize the research accomplishments and new findings.

- a. Adaptive energy efficient algorithms within medium access control (MAC) protocols for wireless networks were developed. A set of scheduling algorithms that dynamically schedule the transmission channel to mobiles based on traffic requests and battery power levels of mobiles were developed. Depending upon network environment, the priority needs of low and high power mobiles may vary. Therefore, a function based on cost/benefit analysis was developed for evaluating algorithm performance for specified system needs. Various system environments are modeled through discrete-event simulation, demonstrating that the proposed power aware scheduling techniques provide low power mobiles with lower packet dropping probabilities through decreased latency and more efficient use of the mobile radio. Also through simulation, it was shown that the power aware scheduling algorithms conserve greater amounts of energy. The research has appeared as a conference paper (invited paper #1 in the publications list) and has been submitted to a journal (journal paper #1).
- b. We consider the data collection problem in wireless sensor networks where, in a round of communication, each sensor node has a packet to be sent to the distant base station. There is some fixed amount of energy cost in the electronics when transmitting or receiving a packet and a variable cost when transmitting a packet which depends on the distance of transmission. If each node transmits its sensed data directly to the base station then it will deplete its power quickly. The LEACH protocol studied elsewhere is based on a clustering mechanism. In our work, we proposed an improved scheme called PEGASIS (Power-Efficient Gathering in Sensor Information Systems), which is a near optimal chain-based protocol that minimizes energy. In PEGASIS, each node communicates only with a close neighbor and takes turns transmitting to the base station, thus reducing the amount of energy spent per round. Simulation results show that PEGASIS performs better than LEACH by about 100 to 200% when varying percentages of nodes die for different network sizes and topologies. PEGASIS performs even better with larger network sizes.

For many applications, in addition to minimizing energy, it is also important to consider the delay incurred in gathering sensed data. We capture this with the "energy x delay" metric and present schemes that attempt to balance the energy and delay cost for data gathering from sensor networks. We studied two new schemes to minimize the energy-delay metric using CDMA and non-CDMA sensor nodes. The

results show that our schemes perform 60 to 280 times better than direct scheme and also outperform the LEACH protocol. (see conf. paper # 3 and journal paper #2 below).

This work was done jointly with Dr. C. S. Raghavendra at Aerospace Corporation in California; and part of the work was done while WSU graduate student, Ms. Lindsey, was a summer intern at Aerospace Corporation during 2000.

- c. Scheduling algorithms for scheduling traffic in wireless data networks with multiple channels per cell were developed. The main objective of the scheduling algorithms was to reduce the computation time while maximizing the utilization of the network resources, thereby improving the system throughput. The research studied two type of algorithms – contiguous allocation based and non-contiguous allocation based. The algorithms were studied for wireless networks with single priority traffic and multiple priority traffic. The research has appeared as a conference paper (conference paper #4) and as a journal (journal paper #3).

- d. A general survey of energy efficient (a.k.a. low power) mechanisms for different layers of the protocol stack was completed and has appeared in a journal (see journal paper #4 below). This survey will serve as a useful starting point for those embarking on research and development in this area.

A more detailed survey of energy-efficient protocols for routing and medium access control functionalities has appeared in a book chapter (see book chapter #1 below). A general survey on energy efficient protocols appeared earlier in a book chapter (book chapter #2).

- e. We consider the problem of multiple access for a sensor network cluster with several hundred nodes. The goal is to develop a scalable protocol that could potentially accommodate thousands of nodes. We proposed a layered architecture where nodes with the same hop-count to the base-station would belong to the same layer. The benefit of this approach comes from the unified method in which routing, medium access control and network organization take place. Detailed performance analysis was conducted to study the performance for more than 500 nodes, and the average delay and network utilization characteristics were studied. The research has been submitted to a conference (conference paper #1).

- f. The problem of routing data packets in large-scale wireless sensor network architecture with multiple base stations, covering a large geographical area, was investigated. The architecture consists of several sensor network clusters, each with its own basestation (BS), with “gateway” sensor nodes in overlapping regions between clusters. The distinct characteristic of this architecture is that the nodes in the backbone graph (represented by the base-stations) are not directly connected, as is typically assumed in 2-layer hierarchies. Instead, the inter-BS communication is also done in a multi-hop manner using the gateway nodes. An inter-cluster routing protocol called Multi-hop Backbone Based Routing protocol (MBBR) is presented. This is used for establishing network connectivity and routing data in this network architecture. The MBBR protocol uses a multi-hop approach with load-sharing among the gateway nodes to reduce energy consumption. MBBR supports peer-to-peer communication among sensor nodes within and across individual sensor network clusters. The proposed architecture and routing mechanisms are studied using a detailed simulation-based performance analysis. The performance of networks with as many as 500 nodes in a 750m x 500m field area was studied, and the key performance bottlenecks were identified. The protocol and the architecture are generic and do not assume any application specific knowledge like data fusion, thus providing great flexibility and generality in their use. The results have been published as a M.S. thesis (thesis #2 below) and are under preparation for a conference submission.

- g. It is expected that wireless networking will soon be embedded into many common everyday objects and devices. It is also expected that battery-operated nodes will be increasingly used to provide various types

of infrastructure communications. Such a network is referred to as a low power multi-hop infrastructure. We have proposed a generalized rendezvous reservation protocol (RRP) which permits systems of this kind to adapt their power consumption in a dynamic fashion. The term rendezvous between two nodes refers to periodic instances when they wake up and exchange messages. Thus a node is awake only during rendezvous instances with its neighbors and goes to sleep at other times. The RRP protocol is connection oriented. The nodes periodically (based on some stochastic arrival process) generate connection requests with a specified quality of service (QoS). A connection setup process is then invoked to establish a path and the node rendezvous rates along the intermediate nodes are selected so as to meet the QoS needs. After a connection is established, the node rendezvous rates may be altered in order to accommodate a new level of service quality. The performance of the RRP protocol for various example network configurations has been studied (see conf. paper # 2 below).

- h. The problem of compensation of wireless channel errors in a medium access protocol based on reservation and scheduling was studied. In this protocol, the base station schedules reservation requests from the mobiles based on packet priorities. When channel errors occur, the scheduled transmission is lost, and it is necessary to compensate these losses in order to meet quality of service requirements. Previous research has considered solutions where the base station keeps track of lost slots and provides compensation slots to accommodate such packets. In this work, however, we consider a solution where the mobile keeps track of the error status of packets and tries to compensate for errors. Each mobile is assumed to generate packets of multiple priorities. The proposed algorithms re-allocate slots among flows within the same mobile host in order to achieve error compensation. The research results have appeared as a conference paper (invited paper #2) and published as a M.S. thesis (see thesis #5 below).
- i. The problem of providing quality of service (QoS) support and routing for wireless networks in the presence of user mobility was studied. The proposed architecture was hierarchical where cells (the basic region of mobile coverage) are organized into QoS/routing domains. The QoS mechanism is based on our earlier work that followed the Integrated services (Intserv) approach with RSVP (ReSerVation Protocol) and CBQ (Class Based Queueing) used for signaling and scheduling respectively. The routing mechanisms developed was a combination of Mobile IP, fast route table updates and proxy ARP (Address Resolution Protocol). These mechanisms were integrated with the above QoS mechanisms. The architecture and mechanisms were implemented and tested in the wireless and mobile testbed. The research has appeared as a journal paper (see journal papers #6 and #7 below).
- j. The design and implementation of an *enhanced* Differentiated Services (Diffserv) architectural framework for providing Quality of Service (QoS) in wireless networks were conducted. The Diffserv architecture was proposed to complement the Integrated Services (Intserv) model for providing QoS in the wired Internet. The research studied whether Diffserv, as defined for wired networks, is suitable for wireless networks. The proposed wireless Diffserv framework took into consideration several factors, including signaling requirements, mobility, losses, lower wireless bandwidth and battery power constraints. It identified the need for supporting signaling and mobility in wireless networks. The framework and mechanisms were implemented in the wireless testbed at Washington State University. Experimental results from this testbed showed the validity of the proposed Diffserv model and also provided performance analyses. The framework was designed to be extensible so that other researchers may use our implementation as a foundation for implementing other wireless network algorithms and mechanisms. The research has appeared as conference papers (conference paper #5 and invited paper #3) and as journal paper (see journal paper #5 below).
- k. A software implementation of Diffserv and Intserv QoS architectures was completed for the FreeBSD operating system. The implementation was shown to work correctly on the wireless testbed. The mobiles

were shown to properly exchange battery power information with the basestation. We tested this feature with a video application, where the basestation dropped selected video frames based on the power levels. This software was made publicly available and it may be used as a foundation for other wireless research that needs a QoS implementation.

- l. A performance analysis of different wireless MAC protocols was conducted. The findings from this analysis indicate that MAC protocols should avoid collisions, needless re-transmissions, and use the transmitter and receiver only as required. The basestation scheduling algorithms should be suitably designed to adapt to mobile power levels. We have also designed and analyzed a low-power MAC protocol for such wireless infrastructure networks. The results have appeared in journal papers (papers #8 and #9).
- m. There exist one or two scheduling algorithms that considered battery power levels. However, these algorithms did not consider the turnaround times of transceiver, and tend to be unfair to mobiles with high battery power. We have developed two energy efficient scheduling algorithms that include turnaround time considerations and are fair in treatment of mobiles, supporting low power users where necessary yet avoiding performance degradation of high power users. The results have been published as a journal paper (paper #11).

## 4 PERSONNEL SUPPORTED

Dr. Krishna Sivalingam, PI

Ms. Jin Ding, M.S/Ph.D., current

Mr. Raghava Kashyapa, M.S., Aug. 2001

Ms. Sripriya Vasudevan, M.S. Aug. 2001

Ms. Stephanie Lindsey, M.S., Dec. 2000

Ms. Lifeng Chen, M.S. Dec. 2000

Ms. Christine Price, M.S., June 2000

Ms. Indu Mahadevan, Ph.D., Oct 1999

Satish Damodaran, M.S., June 1999

Mr. Jian Chuan Lu, Visiting Scholar from China

## 5 PUBLICATIONS

### Journal Publications

1. Christine Price and **K. M. Sivalingam**, "Design and Analysis of Wireless Network Scheduling Algorithms Based on Mobile Battery Levels", (Submitted to), *Computer Communications Journal*, 2001.
2. Stephanie Lindsey, C. S. Raghavendra and **K. M. Sivalingam**, "Data Gathering Algorithms in Sensor Networks using Energy Metrics", (Submitted to), *IEEE Transactions on Parallel and Distributed Systems*, 2001.
3. Satish Damodaran and **K. M. Sivalingam**, "Scheduling Algorithms for Multiple Channel Wireless Local Area Networks", in *Computer Communications Journal*, 2002.

4. Christine E. Jones, **K. M. Sivalingam**, Prathima Agrawal and Jyh-Cheng Chen, "A Survey of Energy Efficient Network Protocols for Wireless and Mobile Networks", in *ACM/Baltzer Journal on Wireless Networks*, vol. 7, No. 4, pp. 343 – 358, 2001.
5. Indu Mahadevan and **K. M. Sivalingam**, "Architecture and Experimental Framework for Supporting QoS in Wireless Networks Using Differentiated Services", in *ACM/Baltzer Journal on Mobile Networks and Applications*, vol. 6, No. 4, pp. 385–395, 2001.
6. Indu Mahadevan and **K. M. Sivalingam**, "Architecture and Experimental Results for Quality of Service in Mobile Networks using RSVP and CBQ", in *ACM/Baltzer Wireless Networks Journal*, Vol. 6, No. 3, pp. 221–234, 2000.
7. Indu Mahadevan and **K. M. Sivalingam**, "A hierarchical architecture for QoS guarantees and routing in Wireless/ Mobile Networks", in *Journal of Parallel and Distributed Computing Special Issue on Wireless and Mobile Computing and Communications*, Vol. 60, No. 4, pp. 510–520, Apr. 2000.
8. **K. M. Sivalingam**, J.-C. Chen, P. Agrawal and M. Srivastava, "Design and Analysis of Low-Power Access Protocols for Wireless and Mobile ATM Networks," in *ACM/Baltzer Wireless Networks Journal*, Vol. 6, No. 1, pp. 73–87, Feb. 2000.
9. J.-C. Chen, **K. M. Sivalingam** and P. Agrawal, "Performance Comparison of Battery Power Consumption in Wireless Multiple Access Protocols", in *ACM/Baltzer Wireless Networks Journal*, Vol. 5, No. 6, pp. 445 – 460, 1999.
10. P. Ramanathan, **K. M. Sivalingam**, P. Agrawal and S. Kishore, "Dynamic resource allocation schemes during handoff for mobile multimedia wireless networks", in *IEEE Journal on Selected Areas in Communications*, Vol. 17, No. 7, pp. 1270–1283, Jul. 1999.
11. J.-C. Chen, **K. M. Sivalingam**, R. Acharya and P. Agrawal, "Scheduling Multimedia Services for a Low-Power MAC in Wireless and Mobile ATM Networks", in *IEEE Transactions on Multimedia*, Vol.1, No. 2, pp. 187–201, June 1999.

#### **Book Chapters**

1. Stephanie Lindsey, **K. M. Sivalingam** and C. S. Raghavendra, "Power-Aware Routing and MAC Protocols for Wireless and Mobile Networks", in *Wiley Handbook on Wireless Networks and Mobile Computing*, Ivan Stojmenovic, Ed., Chapter 19, pp. 407 – 423, John Wiley & Sons, 2002.
2. P. Agrawal, J-C. Chen and **K. M. Sivalingam**, "Energy efficient protocols for wireless networks", in *Wireless Multimedia Network Technologies for the New Millenium*, R. Ganesh, Ed. Kluwer Academic Publishers, 1999.

#### **Invited Papers**

1. Christine E. Jones, **Krishna M. Sivalingam**, Jyh-Cheng Chen and Prathima Agrawal, "Power-Aware Scheduling Algorithms for Wireless Networks", in *International Conference on Intelligent Computing and VLSI*, (Kalyani, India), Feb. 2001.
2. Satish Damodaran and **K. M. Sivalingam**, "Adaptive Scheduling at Mobiles for Wireless Networks with Multiple Priority Traffic and Multiple Transmission Channels", in, *International Conference on High Performance Computing*, (Calcutta, India), Dec 1999.

3. Indu Mahadevan and **K. M. Sivalingam**, "Quality of Service Architectures for Wireless Networks: IntServ and DiffServ Models", in *Workshop on Mobile Computing at the International Symposium on Parallel Architectures, Algorithms, and Networks*, (Perth, Australia), June 1999.

#### **Reviewed Conference Publications**

1. Jin Ding, Raghava Kashyapa and **K. M. Sivalingam**, "Design and Analysis of an Integrated MAC and Routing Protocol Framework for Large-Scale Multi-Hop Wireless Sensor Networks", (Submitted to), ACM Annual International Conference on Mobile Computing and Networking (MobiCom), 2002.
2. Wesley Chen, Terence D. Todd and **K. M. Sivalingam**, "A Rendezvous Reservation Protocol for Low Power Wireless Infrastructure", (Accepted For), *IASTED International Conference on Wireless and Optical Communications (WOC 2002)*, (Banff, Canada), July 2002.
3. S. Lindsey, C. Raghavendra and **K. M. Sivalingam**, "Data Gathering in Sensor Networks using the Energy Delay Metric", in *International Workshop on Parallel and Distributed Computing Issues in Wireless Networks and Mobile Computing*, (San Francisco, CA), Apr. 2001.
4. Satish Damodaran and **K. M. Sivalingam**, "Scheduling in Wireless Networks with Multiple Transmission Channels", in *International Conference on Networks Protocols (ICNP)*, (Toronto, Canada), Nov 1999.
5. Indu Mahadevan and **K. M. Sivalingam**, "Differentiated Services for Wireless Networks: Architecture and Experimental Implementation", in *International Conference on Computer Communication Networks (IC3N)*, (Boston, MA), Oct 1999.
6. P. Ramanathan, **K. M. Sivalingam**, P. Agrawal and S. Kishore, "Resource allocation during handoff through dynamic schemes for mobile multimedia wireless networks", in *IEEE International Conference on Computer Communications (INFOCOM)*, (New York, NY), Mar. 1999.

#### **Graduate Dissertations/Theses**

1. *Dr. Indu Mahadevan*, Ph.D, Oct. 1999. *Dissertation: Quality of service and routing support in wireless and mobile multimedia networks*
2. *Ms. Sripriya Vasudevan*, M.S., August 2001. *Thesis: Cluster based architecture and routing protocol for next generation wireless sensor networks*
3. *Mr. Raghava Kashyapa*, M.S., August 2001. *Thesis: Medium access control and routing protocols for data gathering using wireless sensor networks: design and analysis*
4. *Ms. Stephanie Lindsey*, (U.S. citizen), M.S., November 2000. *Thesis: Energy Efficient Communications for Sensor and Ad Hoc Wireless Networks*
5. *Ms. Lifeng Chen*, M.S., November 2000. *Thesis: Mobile-based Error Compensation Algorithms for Wireless Networks*
6. *Ms. Christine Price*, (U.S. citizen), M.S., May 2000. *Thesis: Power aware scheduling algorithms for wireless networks*
7. *Mr. Satish Damodaran*, M.S., Aug. 1999. *Thesis: Quality of Service scheduling algorithms and security protocols for wireless networks*

## 6 INTERACTIONS/TRANSITIONS

### Participation/presentations at meetings, conferences, seminars, etc.

1. Presented an invited seminar titled "Mobile Ad Hoc Networks: MAC and Routing Primer" at the Department of Defense Laboratory for Telecommunication Sciences, Adelphi, MD. July 2000.
2. Presented a paper at the International Conference on High Performance Computing, (Calcutta, India), Dec 1999.
3. International Conference on Networks Protocols (ICNP), (Toronto, Canada), Nov 1999.
4. Presentation at International Conference on Computer Communication Networks (IC3N), (Boston, MA), Oct 1999.
5. Presentation at Workshop on Mobile Computing at the International Symposium on Parallel Architectures, Algorithms, and Networks, (Perth, Australia), June 1999.
6. Invited panel participant, "Multimedia Communications in Wireless Networks", NSF Workshop on Future Directions in Mobile Computing and Networking Systems, Cincinnati, OH, June 1999.
7. Invited panel participant, "Security in Wireless Networks", NSF Workshop on Future Directions in Mobile Computing and Networking Systems, Cincinnati, OH, June 1999.
8. Invited research presentation at BBN Research (A unit of GTE), "Differentiated Services for Wireless Networks: Framework and Enhancements", Boston, MA, Apr. 1999, Invited by Dr. David Bakken.
9. Invited research presentation at Aerospace Corporation, "QoS Guarantees in Wireless Networks using Differentiated Services", Los Angeles, Mar. 1999. Invited by Dr. C. S. Raghavendra.

### Consultative and advisory functions

1. Member of Technical Program Committee (TPC), IEEE Intl. Conf. on Communications (ICC), Anchorage, Alaska, May 2003
2. Workshop Founder and Co-Chair, First International Workshop on Wireless Sensor Networks and Applications, in conjunction with ACM MobiCom 2002, Atlanta, GA, Sep. 2002
3. Member of TPC, Optical Networking Symposium to be held in conjunction with IEEE Intl. Conf. on Communications (ICC), Anchorage, Alaska, May 2003
4. Technical Program Co-Chair, Third Annual SPIE OptiComm – Optical Communications and Networking Conference, Boston, MA, Jul. 2002
5. Member of TPC, IEEE Symposium on Optical Communications, Chengdu, China, Jul. 2002
6. Member of TPC, IEEE International High Performance Computing Conference (HiPC 2002), Bangalore, India, Dec. 2002
7. Tutorial Chair, Tenth International Symposium on Modeling, Analysis and Simulation of Computer and Telecommunication Systems (MASCOTS), Dallas, TX, Oct. 2002
8. Member of TPC, Publicity Co-Chair, and Publications Co-Chair for ACM Annual International Conference on Mobile Computing and Networking (Mobicom), Rome, Italy, July 2001



9. Member of TPC for ACM Workshop on Modeling, and Simulation of Wireless and Mobile Systems (MSWIM), 1999 – 2002
10. Member of TPC for IEEE International Conference on Network Protocols (ICNP), Riverside, CA, Nov. 2001
11. Visiting Scientist, DoD Laboratory for Telecommunication Sciences, (affiliated with Univ. of Maryland, College Park), Adelphi, MD, July 2000.
12. Visiting Assistant Professor, ECE Dept, McMaster University, Hamilton, ON, Canada, May 2000.
13. Member of TPC, IEEE Intl. Conference on Computer Communications and Networks (IC3N), Las Vegas, NV, Oct. 2000.
14. Member of Technical Program Committee, ACM International Workshop on Wireless Mobile Multimedia (WOWMOM), Boston, MA, Aug. 2000.
15. Tutorial Co-Chair, ACM Fifth Annual International Conference on Mobile Computing and Networking (Mobicom), Seattle, WA, Aug. 1999
16. Ms. Stephanie Lindsey, a graduate student, was invited by Aerospace Corporation, El Segundo, CA (Dr. C. S. Raghavendra) to spend a summer internship during summer 2000. Ms. Lindsey worked on problems to energy efficient communication in wireless sensor networks.

#### **Transitions**

None.

### **7 NEW DISCOVERIES, INVENTIONS, OR PATENT DISCLOSURES**

1. "CDMA Mobile Station Wireless transmission power management with adaptive scheduling priorities based on battery power level", PATENT with P. Agrawal, J. Chen, and S. Kishore, June 2000, Filed by AT&T Corporation.
2. "Adaptive frequency channel assignment based on battery power level in wireless access protocols", PATENT with P. Agrawal and S. Kishore, Oct. 1999, Filed by AT&T Corporation.
3. "Adaptive Scheduling Priorities based on battery power level in wireless access protocols", PATENT with P. Agrawal and M. Srivastava, Oct. 1999, Filed by AT&T Corporation.

### **8 HONORS/AWARDS**

Promoted to Senior Member grade of IEEE in Oct. 2000